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# Lightness of an object under two illumination levels

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**Abstract.** Anchoring theory (Gilchrist et al, 1999 *Psychological Review* **106** 795 – 834) predicts a wide range of lightness errors, including failures of constancy in multi-illumination scenes and a long list of well-known lightness illusions seen under homogeneous illumination. Lightness values are computed both locally and globally and then averaged together. Local values are computed within a given region of homogeneous illumination. Thus, for an object that extends through two different illumination levels, anchoring theory produces two values, one for the patch in brighter illumination and one for the patch in dimmer illumination. Observers can give matches for these patches separately, but they can also give a single match for the whole object. Anchoring theory in its current form is unable to predict these object matches. We report eight experiments in which we studied the relationship between patch matches and object matches. The results show that the object match represents a compromise between the match for the patch in the field of highest illumination and the patch in the largest field of illumination. These two principles are parallel to the rules found for anchoring lightness: highest luminance rule and area rule.

## 1 Introduction

Lightness concerns the perceived black, white, or gray shade of a surface. The basic challenge for theories has been to account for perceived lightness of a surface under different levels of illumination. Helmholtz (1867/1924 – 1925) suggested that the illumination level is unconsciously taken into account but he did not specify exactly how that could be done. More adequate theories emerged with the cognitive revolution in the 1970s. The proposal in those so-called decomposition models (Adelson and Pentland 1996; Bergström 1977) was that the visual system decomposes the retinal image in a manner that is the inverse of the process of image formation by which illumination and reflectance (surface gray level) become entangled. One subclass of such models, called intrinsic image models (Barrow and Tenenbaum 1978; Gilchrist 1979; Gilchrist et al 1983), holds that the image is parsed into overlapping layers representing reflectance and illumination. This is done by extracting luminance ratios from edges in the image, classifying these edges as either reflectance or illuminance edges, and integrating the edges within each of these classes.

These models have turned out to be too good. They fail to explain the varieties of lightness errors that occur in human vision. Such errors are systematic, not random, and because their source lies in the visual system itself, they must be highly diagnostic of our visual software. Gilchrist and his collaborators (1999) proposed a comprehensive model of lightness, called an anchoring model, that claims to provide a unified explanation for a wide range of lightness errors, accounting for veridicality only to the extent that it exists.

The anchoring model deals explicitly with both simple images and complex images. A simple image is defined as an image composed of two surfaces that fill the observer's entire visual field. Empirical work has shown that the computation of lightness in simple images can be exhaustively described by three rules. (i) The region of highest luminance is seen as white, while the lightness of the darker region depends simply on the luminance ratio between the two regions (Li and Gilchrist 1999); in addition, these computations are influenced both by (ii) the luminance range within the image and (iii) the relative area of a target (Gilchrist et al 1999). The second rule reflects the tendency of the visual system to expand or compress the perceived range to preferred 30 : 1 (ie the range between black and white) when the visual scene has smaller or larger luminance range. The third rule refers to the tendency to perceive regions lighter than they are when they cover more than 50% of the visual scene.

The model makes a crucial claim regarding the relationship between simple and complex images. According to this claim, called the applicability assumption, the three rules of anchoring that describe lightness in simple images can be applied within frames of reference embedded within complex images. These frames of reference are defined by two main segmentation factors: (i) fuzzy boundaries (penumbrae) and (ii) depth boundaries (occlusion edges and corners). Edge junctions and Gestalt grouping factors serve as weaker segmentation factors. These frameworks are not autonomous, however; there is cross-talk between them. Here the model incorporates the important principle of co-determination proposed by Kardos (1934). Any target surface within a complex image is said to belong simultaneously to at least two frameworks: the global framework, which is the whole visual field, and one or more local, embedded frameworks. A separate lightness value is computed for that surface in each of its parent frameworks, and its final perceived lightness is a weighted average of these. This weighting depends on two factors originally uncovered by Katz (1935): the size and degree of articulation of each local framework.

The experiments we report were motivated by a gap in the anchoring model, according to which the retinal image is segmented into frames of reference that roughly correspond to fields of illumination. But many objects in natural scenes do not lie exclusively within a single field of illumination. Rather, they lie partly in one field of illumination and partly in another, as illustrated in figure 1. Such a multi-lit object, as we will call it, straddles two fields of illumination and is divided into two regions, one darker and one lighter, by an obvious illumination boundary cutting across it. We will refer to the separate regions of illumination on the object as patches.

Economou et al (1998) reported a paradox that occurs with a multi-lit object. Observers report that the object has a single shade of gray, but when asked to match the exact gray shade of the two patches, they give different values. This is not a failure of instructions: expert observers do the same thing. The paradox is not limited to the laboratory conditions (ie artificial lights of limited luminance range, small objects). Agostini (2003) describes the very same finding when observers were asked to match the shades of a building wall partially in sunlight and partially in shadow.

Perhaps it is inappropriate to ask observers to match the lightness of a patch. A patch, after all, is the intersection of a region of homogeneous illumination and a region of homogeneous reflectance. It is certainly not an object by itself. Lightness, on the other hand, is the property of an object. From this perspective we could forget about patches altogether and forget about the paradox. However, the anchoring model, because it computes lightness by applying a given anchor uniformly throughout a field of illumination, anticipates the paradox. That is, a multi-lit object is assigned two lightness values by the model, one for each of the patches, because each patch lies within a different field of illumination. Whether or not it is appropriate to take lightness matches for patches, the anchoring model rather accurately predicts these matches. What the model fails to do, in its current form, is to predict a single value for the whole multi-lit object.

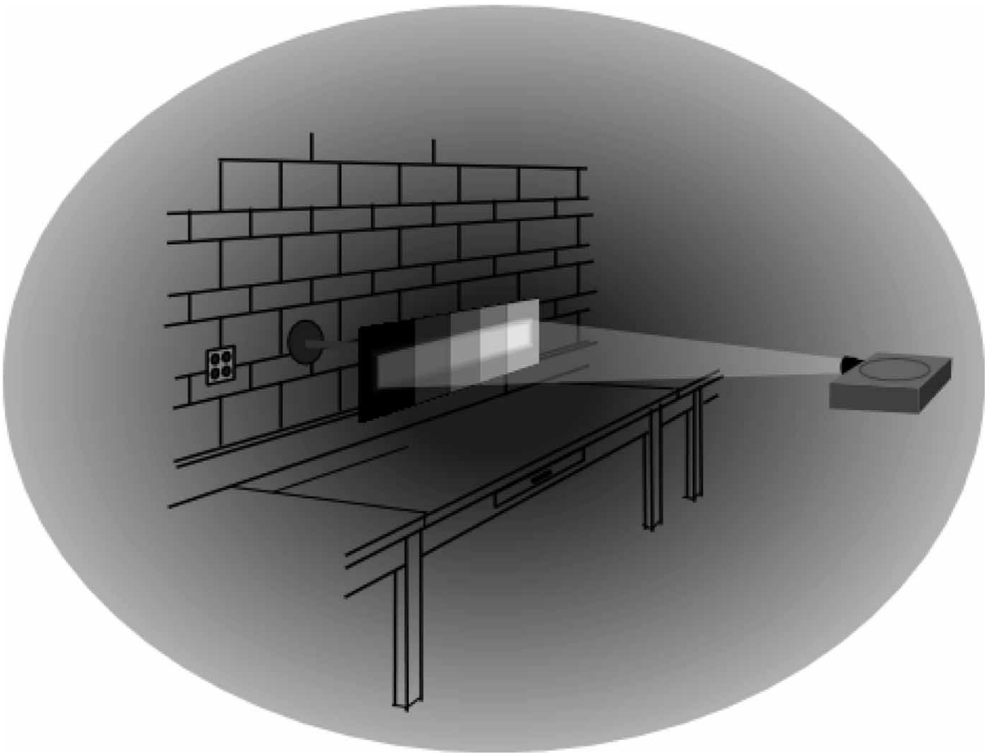

**Figure 1.** Laboratory scene showing five-rectangle display with a spotlight in the center. Inset: diagram of display.

We conducted a series of experiments in which we took lightness matches both for patches and for objects. Our question was "is there a systematic relationship between patch matches and object matches, and, if so, what is the relationship?" Such a systematic relationship would presumably allow an extension of the anchoring model to multi-lit objects.

## 2 Methods

### 2.1 *Subjects*

The subjects in all of the experiments were undergraduate students at Rutgers University who volunteered to satisfy a course requirement. All of the subjects had normal or corrected-to-normal vision.

### 2.2 *Display*

The display consisted of five adjacent rectangles (as presented in figure 1). The rectangles were made of matte Color-Aid paper. Each rectangle was 22 cm in height and 11 cm in width. The five rectangles were arranged in order of increasing reflectance, in roughly equal steps on a logarithmic scale: 0.50, 0.85, 1.21, 1.63, 1.95. The rectangles were mounted on cardboard, creating a 55 cm by 22 cm display. This display was suspended in midair, 94 cm above the floor and 78 cm away from the back wall, and supported by an aluminium rod that extended from the back wall but was hidden from view by the display itself.

### 2.3 *Laboratory arrangements*

The subject was seated facing the display at a viewing distance of 390 cm. The visual angle of the whole display was 8.1 deg in width by 3.2 deg in height. The whole lab (room) was normally illuminated by a set of ceiling fluorescent lights. The luminance of a white surface in room illumination at the location of the display was 19.4 cd $m^{-2}$.

Either a spotlight or a shadow (special illumination) was projected onto a part of the display (as shown in figure 1, with the spotlight in the middle of the display).

The spotlight was created with a Kodak Electrographics slide projector, model 8-2 (lens: 100 mm – 150 mm, *f* 3.5), mounted near the ceiling, 282 cm from the display. One part of the display was covered with this spotlight and the rest of the display remained in room illumination.

For projecting a shadow, the room lights were replaced by a single bare 1000 W quartz halogen light mounted inside a metal waste-paper can mounted in a horizontal position, 140 cm below the ceiling and 290 cm away from the display, so that the open end faced the display and the wall behind it. The waste-paper can prevented direct illumination of the other three walls of the laboratory, in order to minimize indirect illumination of the display. A paper shadow caster, cut to provide the desired shape of shadow, was attached to a transparent acrylic panel suspended vertically from the ceiling, 93 cm away from the light.

The special illumination was approximately 30 times brighter (in the case of the spotlight) or 30 times dimmer (in the case of the shadow) than the room illumination. This was calibrated by adjusting the illumination levels in each experiment so that a black paper standing in the higher illumination was equal in luminance to a white paper standing in the lower illumination.

There were two possible locations of special illumination: center and annulus. The center region was 11 cm in height. The two regions had roughly equal areas on the display and were bordered by an obvious penumbra 1.8 cm wide.

### 2.4 *Measuring scale*

A 33 cm by 10 cm Munsell chart was used for lightness matches. It consisted of 16 chips spanning a range from black through different shades of gray to white, in equal steps. Each shade was labeled with a number (from 2 to 9.5). The scale was placed in a box in front of the observer. The box had its own illumination that was kept constant in all experiments. Luminance values on the scale had a range from 26.6 to 334 cd $m^{-2}$.

### 2.5 *Procedure*

The lighting conditions for each experiment were set before the subject arrived. The subject was asked to describe the display in his or her own words (self-report). The description was considered complete as soon as the subject mentioned that she/he saw five different shades (reflectance values), two different illumination levels, and the sign (spotlight or shadow) of the special illumination was correctly reported. In all of the conditions the self-report corresponded to physical conditions of the stimulus and will not be discussed further. The subject was then shown an outline of the display (inset in figure 1) and asked to select a sample from the chart that matched each target surface in the stimulus display.

### 2.6 *Design*

Two groups of ten subjects participated in each experiment. One group of subjects was asked to match the shades of each whole rectangle and the other group matched the patches. Using separate groups of subjects enabled us to have naive subjects for each matching task.

The order of regions subjects were asked to match was balanced in all of the experiments. Half of the subjects started from the white and the other half from the black rectangle. Additionally, half of the subjects first matched the center region and the other half matched the annulus region first. No order effect due to this procedure was noticed after the first experiment; however, the same procedure was kept in the subsequent experiments.

## 3 Experiments

The experiments were designed to investigate the relationship between the object matches and patch matches. In that respect there are two logical outcomes, that the object matches are related to the patch matches or that they are not related. If they are related, there are two simple possibilities. First would be that object matches are related only to one set of patches. Another is that they are related to both sets of patches, the object match being a simple average of the values for the two constituent patches.

There are other more complicated outcomes; however, we began with the three general hypotheses about the relationship between the object matches and the patch matches.

*Hypothesis 1*: Object lightness is equal to the lightness of one of the two sets of patches.
*Hypothesis 2*: Object lightness is equal to the simple average of the two sets of patches.
*Hypothesis 3*: Object lightness is not related to the patch matches.

### 3.1 *Experiment 1: Center shadow*

A center shadow was cast onto the display. The results are shown in figure 2. Both axes are logarithmic scales. Each data point represents the average value for ten observers for each of the five shades. The thin black line represents the actual values for all shades.

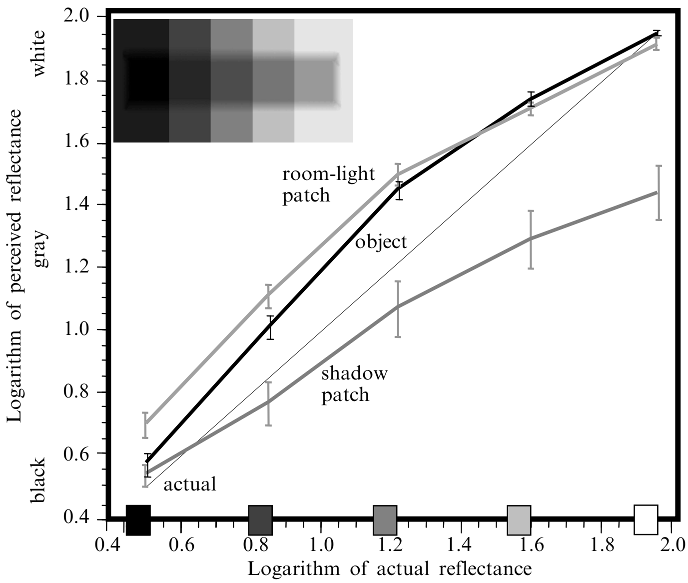


**Figure 2.** Results of experiment 1. Thin line labeled 'actual' represents veridical values. The gray lines are matches for patches in special and room illumination. The black line with error bars gives matches for object. The icon represents display and lighting conditions. (Logarithmic transformation was performed on percentage reflectance values.)

First of all, the results confirm the previous findings (Economou et al 1998), that subjects give two different lightness matches for the patches in different illumination. An ANOVA showed that, for every rectangle, the match for the patch in room illumination was significantly lighter than the match for the patch in shadow ($F_{1,9} = 35.31$, $p < 0.05$). This kind of ANOVA was performed in all of the subsequent experiments and the patches in the higher illumination always appeared significantly lighter than the corresponding patches in lower illumination. But, because these differences were not of interest for our study, they will not be reported further.

Object matches (made to the whole rectangle) were in good agreement with the patches in the higher room illumination. Two additional ANOVAs were performed: the first one to test the difference between the object and its patch in room light and the second one to test the difference between the object and its shadowed patch. These analyses used a between-subjects design, because the two sets of data came from two different groups of observers: (i) the group that judged patches, and (ii) the group that judged objects. Each was a two by five ANOVA comparing two types of match (patch versus object) and five shades of gray. The factor for gray shade, which was significant in all cases, as one would expect, will not be further reported as it is irrelevant to the hypotheses we tested. The first ANOVA showed that the object matches were not significantly different from the patches in room illumination ($F_{1,1} = 3.16$, $p = 0.09$). To reduce the risk of a Type 1 error, an a posteriori Scheffé's test was used for each object. The object matches were not significantly different from the patches in room illumination (all $ps > 0.20$), except for black, which was significantly darker ($F_{1,18} = -0.14$, $p < 0.05$).

The second ANOVA showed that the object matches were significantly lighter than the corresponding patches in the shadowed region ($F_{1,1} = 23.46$, $p < 0.05$). Scheffé's test showed that object matches were significantly lighter than the patches in shadow, for all shades except black (white: $F_{1,18} = 0.54$, $p < 0.05$; light-gray: $F_{1,18} = 0.47$, $p < 0.05$; middle-gray: $F_{1,18} = 0.42$, $p < 0.05$; dark-gray: $F_{1,18} = 0.24$, $p < 0.05$; black: $F_{1,18} = 0.02$, $p = 0.99$).

The only shade that did not follow the overall pattern of data was black. As will be seen, this pattern of results occurred in several of our experiments, specifically in all of the experiments where the shadow covered half of the display. We have no coherent explanation for this peculiar result, but it reminds one of Katz's (1935) concept of pronouncedness. Katz argued that white and light-grays are more pronounced in high illumination while blacks and dark-grays are more pronounced in low illumination. Matching the black rectangle to a black on the scale rather than to the value of the patch of black in the room illumination has the effect that matches for the five rectangles span the entire range of the scale. The object matches thus avoid the compression that characterizes the patches.

Overall, these findings support the first hypothesis. Four out of the five object matches were consistent with the patches in the room illumination. This pattern of results and analysis of the stimulus conditions suggested several more specific hypotheses:

*Hypothesis 4*: Figure/ground: object matches agree with patches in the background region of the illumination (the annulus), not the figural region (center). This hypothesis was essentially motivated by Rubin's (1921) idea about figure/ground qualities. However, his concept of border ownership (Nakayama and Shimojo 1990) was not applied to illumination levels before. The illumination edge in our display belongs to the shadowed region in the middle. Had it been a spotlight instead of a shadow, the border would have belonged to the spotlight. In short, the border is not assigned on the basis of the illumination level, but on the basis of size, closure, and location, just as in Rubin's proposal.

*Hypothesis 5*: Largest area of illumination: object matches agree with patches in the largest field of illumination (ie the region in room light). This hypothesis was motivated by Katz's (1935) idea of prevailing illumination.

*Hypothesis 6*: Area of highest illumination: object matches agree with patches in the highest illumination. Apart from being background and region of the prevailing illumination, this illumination level was also region of the highest illumination level.

### 3.2 *Experiment 2: Annular shadow*

In experiment 2 we tested the importance of figure/ground qualities (hypothesis 4) against the other two hypotheses. Everything was the same as in the previous experiment except that the shadow was reallocated from the center to the annulus region. If hypothesis 4 were correct, the annulus region would still determine object lightness.

The results are shown in figure 3. Object matches were again in good agreement with the patches in the room illumination. Two between-subjects ANOVAs were performed:

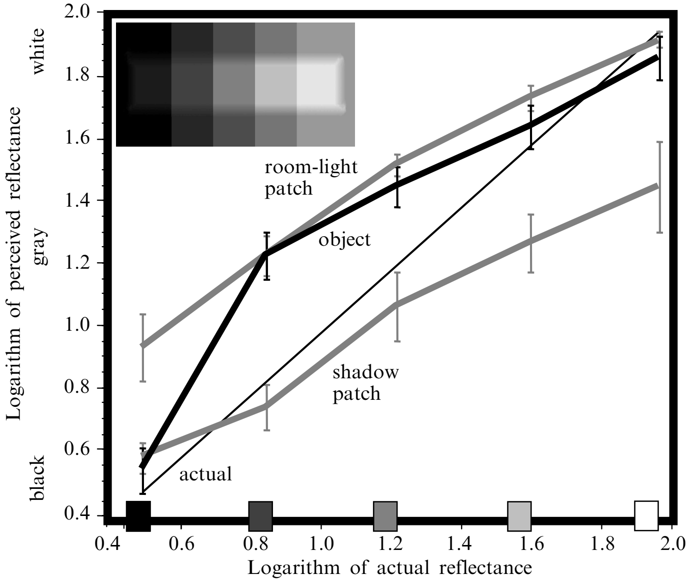


**Figure 3.** Results of experiment 2. For legend see caption to figure 2.

again one to test the difference between the object and the patch in the room light and the second one to test the difference between the object and the shadowed patch.

The first ANOVA showed that the object matches were not significantly different from the corresponding patches in the room illumination ($F_{1,4} = 198.08$, $p < 0.05$). The same results were obtained with Scheffé's test (all $p$s $> 0.20$) except for black, in which case the object match was significantly darker than the patch in room illumination ($F_{1,18} = -0.26$, $p < 0.05$).

The second ANOVA showed that the object matches were significantly lighter than the corresponding patches in the shadow ($F_{1,1} = 14.34$, $p < 0.05$). Scheffé's test was significant for all shades but black. The results are for white $F_{1,18} = 0.07$, $p < 0.05$; for light-gray $F_{1,18} = 0.07$, $p < 0.05$; for middle-gray $F_{1,18} = 0.07$, $p < 0.05$; for dark-gray $F_{1,18} = 0.07$, $p < 0.05$; for black $F_{1,18} = 0.67$, $p = 0.99$.

The data analysis showed that the object lightness (for all shades but black) was not determined by the annulus region of the display. Again, it was determined by the region outside of the shadow. Apparently, the spatial arrangement of the special illumination did not play a role in this stimulus configuration. This result rejects hypothesis 4.

### 3.3 *Experiment 3: Center spotlight*

Experiment 3 pitted hypotheses 5 and 6 against each other. In this experiment, instead of a shadow, a center spotlight was cast on the display. Hence one set of patches was in the largest area of illumination (annulus region) and the other set of patches was in the highest illumination (center region). If hypothesis 5 were correct the annulus region would determine the object lightness; if hypothesis 6 were correct the center region would determine it.

To accommodate the position of the projector, the display was mounted in midair, 135 cm above the floor and 48 cm away from the back wall, but the observer was moved closer to the display to keep the visual angle of the display constant.

As can be seen from the results (figure 4), object lightness was a compromise between the two sets of patches. Additionally, the results for black do not seem to differ from the rest of the shades. The first ANOVA showed that the object matches were not significantly different from the corresponding patches in the room illumination ($F_{1,1} = 3.00$, $p = 0.10$). However, Scheffé's test was significant for middle-gray

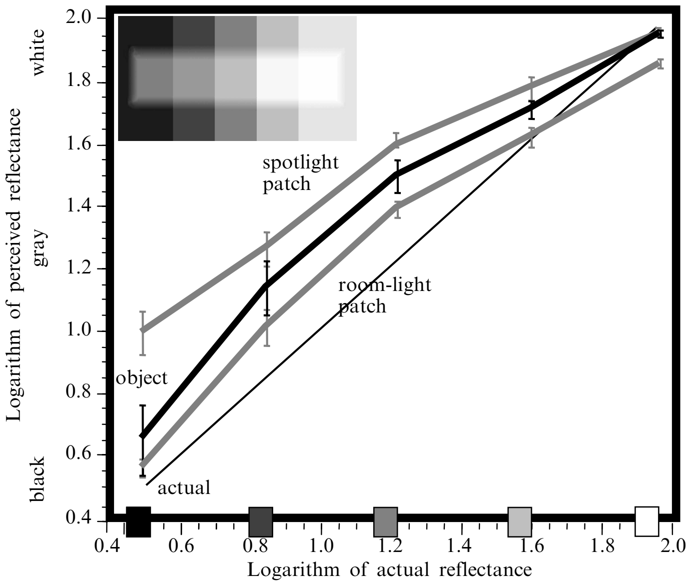


**Figure 4.** Results of experiment 3. For legend see caption to figure 2.

($F_{1,18} = 0.10$, $p < 0.05$), which appeared significantly lighter than the corresponding patch in the room illumination. Other matches were not significantly different (all $p$s $> 0.20$). The second ANOVA showed that the object matches were significantly darker than the corresponding patches in the spotlight ($F_{1,1} = 4.39$, $p < 0.05$). However, Scheffé's test was significant only for black ($F_{1,18} = -0.32$, $p < 0.05$) while the other comparisons did not reach significance (all $p$s $> 0.20$).

This result did not agree with either of the two hypotheses (hypothesis 5 and hypothesis 6) but suggested that object lightness is determined both by highest illumination and largest area. We will call this hypothesis 7. There is another possible interpretation of the results for this experiment, consistent with hypothesis 5. The two illumination levels had almost equal areas on the display. Thus, if the largest area is defined solely in terms of area on the display (as opposed to area in the whole room), a compromise should have been expected. However, this interpretation was already contradicted by the results from the first two experiments. Hypothesis 7 is little more than a description of the obtained data. Nevertheless, it suggests two separate factors: largest area and highest illumination, each of which could be tested separately.

The largest area of illumination can be defined in three different ways, as (i) the largest area in the whole visual scene (global area), (ii) the largest area on the whole display of five rectangles (area on the display), and (iii) the largest area on each of the five rectangles that constitute the display (area on the object).

In the first three experiments 'the largest area' was used in its first meaning: the largest area of the whole scene (ie whole room). This further implies that the region of the display standing in room illumination was perceptually grouped with the rest of the scene and this grouping was based on the same illumination level. This is suggested by the comparison between experiments 2 and 3. The annular shadow and the center spotlight were locally identical stimuli: they both had a full range of shades (ie from black to white), they had an approximately 30 times brighter region of illumination in the center of the display, and each of the two illuminations covered half of the display. However, the obtained patterns of results for the two experiments were very different from each other. This could only be accounted for if the illumination regions outside of the display influenced the perceived shades on the display.

The problem of the different definitions of area (second and third definition) was investigated in experiments 4, 5, and 6, and experiment 7 dealt with the role of the highest illumination.

In the first three experiments, areas on the display and areas on the objects were almost equal and in that respect neutralized. In experiments 4 to 7, both the area on the display and on the object were varied in order to test these two meanings of area.

3.4 *Experiment 4: Narrow spotlight*

The whole experimental set up was the same as in experiment 3 except that the height of the center spotlight was decreased to 6 cm (visual angle: 0.85 deg). This variation left only about one-fourth of the display in the special illumination (as opposed to one-half in experiment 3). If area on the display (second definition of area) plays a role, then the change of the spotlight area on the display will shift object matches towards those of the annulus region. But if the area on the display does not play a role and the only meaning of area is global area, object matches will again be a compromise.

The results are shown in figure 5. As can be seen, object matches were again in good agreement with the patches in the room illumination. The first ANOVA showed that the object matches were not significantly different from the corresponding patches in the room light ($F_{1,1} = 2.01$, $p = 0.17$). Scheffé's test showed that this difference was not significant for any of the shades (all $p$s $> 0.20$). The second ANOVA showed that the object matches were significantly darker than the corresponding patches in the spotlight ($F_{1,1} = 40.36$, $p < 0.05$). Scheffé's test showed that object matches for middle-gray, dark-gray, and black all appeared significantly darker than the corresponding patches in the spotlight. The results are for white and light-gray ($p$s $> 0.20$); for middle-gray $F_{1,18} = -0.22$, $p < 0.05$; for dark-gray $F_{1,18} = -0.45$, $p < 0.05$; for black $F_{1,18} = -0.55$, $p < 0.05$.

These results show that object lightness was completely determined by the largest area on the display. There was no compromise between the regions of largest and highest illumination. In this condition, the field of the largest area of illumination not only covered most of the global scene but also most of the display and therefore outweighed the area of highest illumination. It can be concluded that, in addition to global area, the largest area of illumination on the display also plays a role.

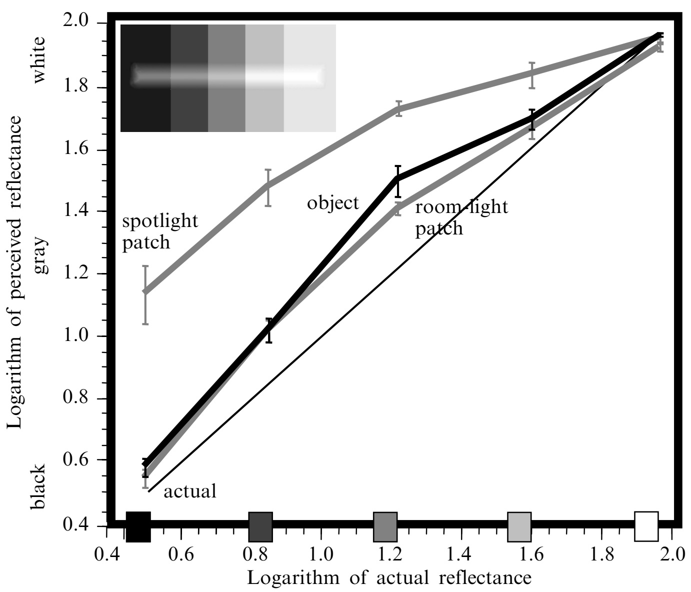


**Figure 5.** Results of experiment 4. For legend see caption to figure 2.

### 3.5 *Experiment 5: Display on the wall*

There is another way to manipulate the area on the display. Instead of decreasing the spotlight size, we increased the size of annular region by putting the display directly on the back wall. In this case, the display is a part of the huge wall behind it and the whole wall becomes a part of the annular region of the display.

As was shown in experiment 3, the observed object lightness is a compromise between the illumination of the largest area (annular region in the room illumination that was grouped with the rest of the lab) and the illumination of the highest intensity (center region with the spotlight). However, we hypothesized that decreasing the distance between the display and the back wall would strengthen the grouping with the rest of the lab. In the most extreme case when the display is coplanar with the back wall, it can be expected that the largest area of illumination would overrule the highest illumination. Consequently, object lightness would be completely determined by the annular region of the display that becomes a part of the global area.

The arrangements were the same as in experiment 3 except for two changes. The display was attached to the wall and observers were moved closer to the display to keep the visual angle of the display the same as in experiment 3. The results are given in figure 6. The first ANOVA showed that the objects were not significantly different from the corresponding patches in the room light ($F_{1,1} = 1.04$, $p = 0.32$). Scheffé's test was not significant for any of the shades (all $p$s $> 0.20$). The second ANOVA showed that the object matches were significantly darker than the corresponding patches in the spotlight ($F_{1,1} = 7.25$, $p < 0.05$). Scheffé's test was significant for dark-gray ($F_{1,18} = -0.28$, $p < 0.05$) and black ($F_{1,18} = -0.49$, $p < 0.05$) as the two shades appeared significantly darker as objects than the corresponding patches.

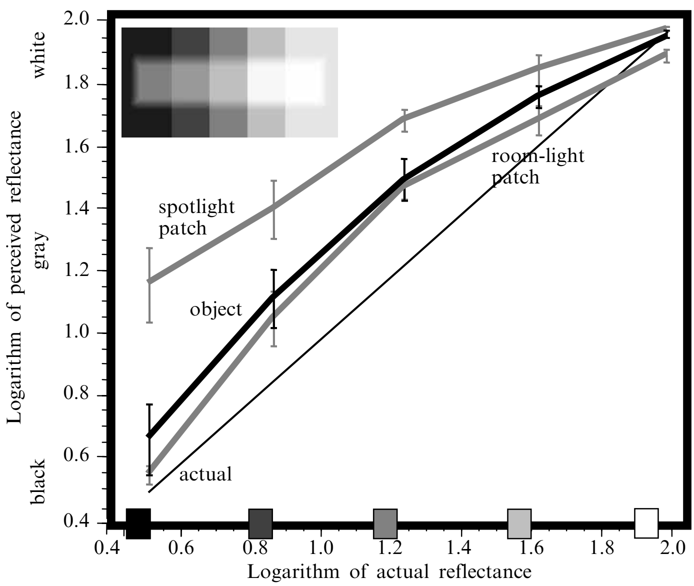


**Figure 6.** Results of experiment 5. For legend see caption to figure 2.

Object lightness was consistent with the lightness of the patches outside of the spotlight. Again, unlike in experiment 3, there was no compromise between the largest and highest illumination. The region outside the spotlight was no longer just the half of the display, but it acquired the area of the whole wall. In that respect, the stimulus condition and the pattern of obtained results resembled the condition and the results from experiment 4 (narrow spotlight). Experiments 4 and 5 represent two different ways of putting more weight on the largest area of illumination.

### 3.6 *Experiment 6: Thick shadow*

Although the results of experiments 4 and 5 showed that the largest area on the display plays a role, the area of the highest illumination was significantly changed in the global scene owing to the decrease of the spotlight size. The same question about the influence of the display area could be investigated with a setup that did not practically change the area of the highest illumination in global scene.

In experiment 6, the annulus shadow was enlarged to cover most of the display, leaving only a thin stripe (6 cm in height) of the room illumination in the center region. Other than that, the conditions were the same as in experiment 2. This manipulation did not practically change illumination conditions in the whole scene, because the area of the whole lab remained much larger than the area of the display. However, the increase in the shadow size (from one-half of the display to three-fourths of the display) was substantial on the display itself.

If the largest area of illumination on the display played no role, then the center region in the room illumination (highest illumination and largest area of illumination in the whole scene) would determine the object matches (ie same results as in experiment 2). If the largest area on the display also plays a role, as experiments 4 and 5 suggest, then object lightness should be a compromise between the largest area on the display and the highest illumination. It was not expected that object lightness would be completely determined by the shadowed region, since the tiny stripe of room illumination was not only the highest illumination in the scene but also region of the largest area of illumination in the whole scene. The results are shown in figure 7. The first ANOVA showed that the objects appeared significantly darker than the corresponding patches in the room illumination ($F_{1,1} = 4.57$, $p < 0.05$) though Scheffé's test did not reach significance for any of the individual shades (all $p$s $> 0.20$). The second ANOVA showed that the object matches were significantly lighter than the corresponding patches in the shadow ($F_{1,1} = 7.22$, $p < 0.05$). Scheffé's test showed that the light-gray ($F_{1,18} = 0.28$, $p < 0.05$) and middle-gray ($F_{1,18} = 0.28$, $p < 0.05$) objects were significantly lighter than their shadowed patches.

These results suggest that object lightness is a compromise between the regions of highest and largest illumination. In comparison to experiment 2 (annular shadow), object

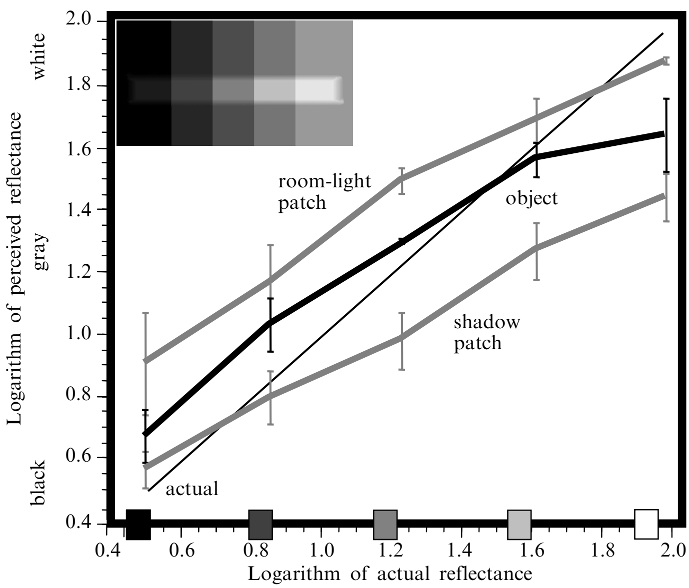


**Figure 7.** Results of experiment 6. For legend see caption to figure 2.

lightness values shifted away from those of the region outside of the shadow, proving that area on the display (second definition of area) plays a role in object lightness. The pattern of obtained results resembled the results from experiment 3 (center spotlight) in which largest area and highest illumination were pitted against each other, leading to a compromise. The situation is the same in this experiment: largest area on the display is pitted against largest area in the whole scene and highest illumination. The result is a compromise. And although the shadow is neither the highest illumination nor region of the global illumination, its increased area on the display gave it more weight.

3.7 *Test of the area on the object—experiment 7: zig-zag condition*

The third possible definition of largest area is area on each object itself. In this experiment we tested the role of largest area of illumination on the object. The rectangles on the display were displaced so as to form a staggered pattern (as depicted in the lower corner of figure 8). A spotlight was cast on the upper half of the display. The staggered pattern enabled the spotlight to cover different areas on each of the objects while still covering half of the display as a whole.

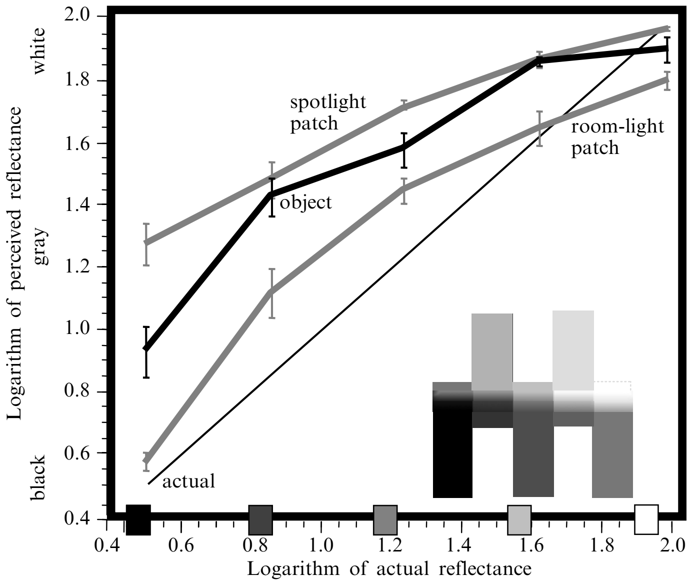


**Figure 8.** Results of experiment 7. For legend see caption to figure 2.

The results are given in figure 8. The first ANOVA showed that the objects appeared significantly lighter than the corresponding patches in room illumination ($F_{1,1} = 17.09$, $p < 0.05$). Scheffé's test showed that object matches for light-gray, dark-gray, and black were significantly lighter than the patches in room illumination. The results are: for middle-gray $F_{1,18} = 0.31$, $p = 0.27$; for dark-gray $F_{1,18} = 0.31$, $p < 0.05$; for black $F_{1,18} = 0.35$, $p < 0.05$. The second ANOVA showed that the objects appeared significantly darker than the corresponding patches in the spotlight ($F_{1,1} = 6.48$, $p < 0.05$). In Scheffé's test, only the black rectangle appeared significantly darker than its lighted patch ($F_{1,18} = -0.34$, $p < 0.05$).

An additional one-way $t$-test (with non-equal variances) was performed to compare the object matches from experiment 3 (center spotlight) with the object matches from this experiment. The results showed that the two rectangles mostly covered with spotlight (dark-gray and light-gray) in experiment 7 appeared significantly lighter than the same two rectangles in experiment 3, but this was not true for the remaining three rectangles (white $t_{18} = 1.373$, $p = 0.100$; light-gray $t_{18} = -4.357$, $p < 0.05$; middle-gray $t_{18} = -1.036$, $p = 0.157$; dark-gray $t_{18} = -2.706$, $p < 0.05$; black $t_{18} = -2.004$, $p = 0.31$).

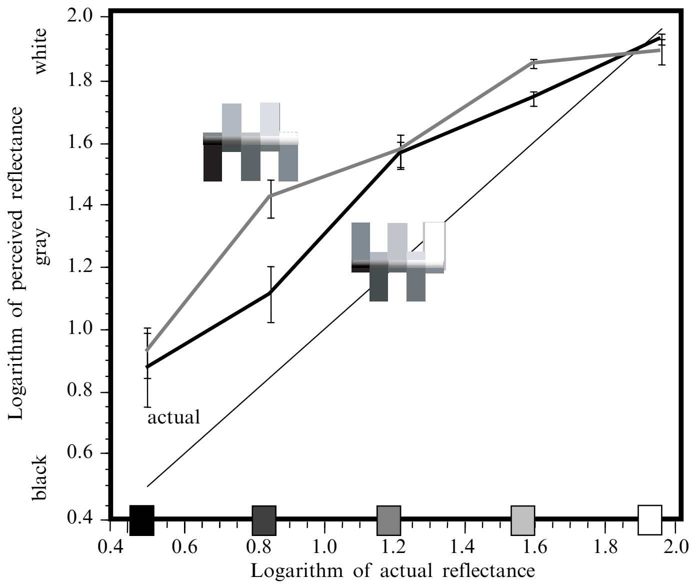


**Figure 9.** Results for both conditions in experiment 7. For legend see caption to figure 2.

In the control condition the display was inverted, so that the other three rectangles (white, middle-gray, and black) extended mostly into the spotlight while the remaining two rectangles extended mostly into room illumination. Figure 9 presents the results of the original zig-zag condition and this control condition. Both displays showed the same pattern of results for the object matches.

The first ANOVA for control condition showed that the objects appeared significantly lighter than the corresponding patches in room illumination ($F_{1,1} = 13.91$, $p < 0.05$). Neither of the Scheffé's tests reached significance (all $p$s $> 0.20$). The second ANOVA showed that the objects did not appear significantly darker than the corresponding patches in the spotlight ($F_{1,1} = 0.31$, $p = 0.58$). Scheffé's test did not reach significance (all $p$s $> 0.20$).

In summary, those rectangles mostly covered in room illumination showed a compromise between the values of their two patches, like in the center spotlight condition (experiment 3). For those rectangles mostly covered with the spotlight, the lightness matches shifted towards those of the patches in the spotlight. This experiment confirms the role of the largest area on the object itself.

### 3.8 *The highest illumination—experiment 8: spotlight/shadow*

Experiments 3, 4, 5, 6, and 7 demonstrate the influence of the largest area of illumination as the first part of hypothesis 7 suggests. The second part of hypothesis 7, concerning the role of the region of highest illumination, was tested in experiment 8.

In order to neutralize the largest-region-of-illumination factor, the upper half of the standard five-rectangle display was covered with a shadow and the lower half of the display was covered with a spotlight. Therefore the whole display was covered with special illumination. This manipulation neutralized the three levels of area previously studied: (a) the object matches could not follow the larger area on the object because the areas on each object were equal; (b) the object matches could not follow the larger area on the display because the areas were equal; (c) the object matches could not follow the larger area in the whole field because neither set of patches was in the prevailing illumination. Therefore this condition isolated the highest illumination as the only possible factor in determining object lightness. The results are given in figure 10. The first ANOVA showed that the objects were not significantly different from the corresponding patches in the spotlight

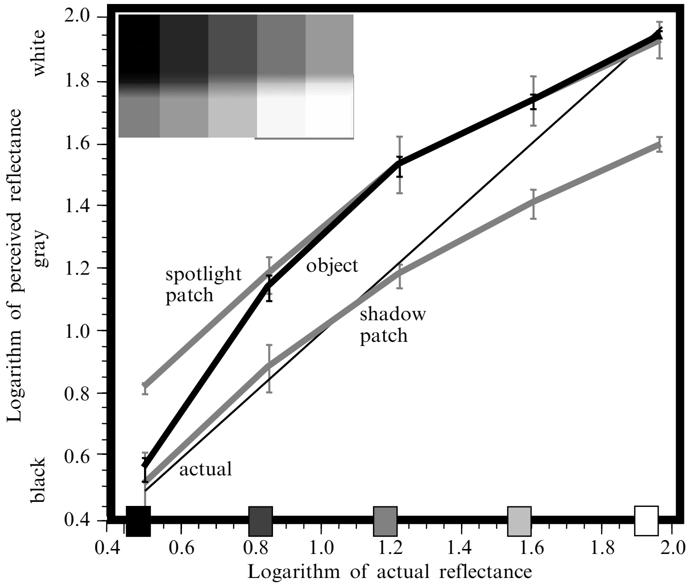


**Figure 10.** Results of experiment 8. For legend see caption to figure 2.

($F_{1,1} = 1.81$, $p = 0.19$). Scheffé's test showed that only the black object appeared significantly darker than its patch in the spotlight ($F_{1,18} = -0.26$, $p < 0.05$). The second ANOVA showed that the object matches were significantly lighter than the corresponding patches in the shadow ($F_{1,1} = 15.68$, $p < 0.05$). Scheffé's test found significance for all the shades except black (for white $F_{1,18} = 0.30$, $p < 0.05$; for light-gray $F_{1,18} = 0.32$, $p < 0.05$; for middle-gray $F_{1,18} = 0.34$, $p < 0.05$; for dark-gray $F_{1,18} = 0.25$, $p < 0.05$).

As the analysis shows, with area neutralized, object lightness (for all shades but black) was determined by the highest illumination. In contrast to experiment 3, where object lightness was a compromise between the spotlight region and the region in the room illumination, in this experiment object lightness was not a compromise between higher and lower illuminations.

## 4 Discussion

We have examined the lightness of an object divided by an illumination border, a question without an answer in anchoring theory (Gilchrist et al 1999). Lightness values for the patches of that object can be predicted by the original rules of anchoring theory. In order to account for multi-lit objects within a modified anchoring theory, it was necessary to discover the relationship between matches made to the separate patches and matches made to the object as a whole. The results show that the object matches cannot necessarily be identified with either set of patches. Instead, the visual system applies two rules for computing the lightness of the whole object. The two rules are: object matches follow the patches in the largest region of illumination and those in the region of highest illumination.

When one set of patches happens to lie in a region of illumination that is both highest and largest, as in the first two shadow experiments, the object matches agree with that set of patches (ie patches in room illumination). However (as in experiment 3: center spotlight) when one set of patches lies in the largest area of illumination (patches in the room light) and the other set of patches lies in the region of highest illumination (patches in the spotlight), the two rules are pitted against each other and consequently object lightness is a compromise between the values for the two sets of patch matches. In those experiments that included a shadow (experiments 1, 2, and 8) the black rectangle did not follow these rules but always went with the patch in the shadow. We cannot explain this anomaly.

The largest area of illumination was defined in three possible ways in these experiments (i) the largest area in the global scene, (ii) the largest area on the display itself, and (iii) the largest area on an individual rectangle. Experiment 3 (center spotlight) demonstrates that the largest area in the global scene is important. The center region (spotlight) is the highest area of illumination. The annulus region covers the other half of the display. Consequently it plays a role in the compromise only because it is the region of the largest area of illumination in the global scene. The comparison between experiment 3 (center spotlight) and experiment 2 (annular shadow) is very instructive in this regard. Apart from absolute luminances and apart from the surrounding context, the two displays have the same pattern of illumination. But the results are very different. In the annular-shadow condition, object lightness is consistent with the patches in room illumination, and in the center-spotlight condition, it is a compromise. The reason, of course, is that in experiment 2 the higher illumination is also region of the largest field of illumination in the global scene and in experiment 3 it is not.

The importance of the area on the display itself can be seen by comparing experiment 4 (narrow spotlight), experiment 5 (display on the wall), and experiment 6 (thick shadow). When the area of a spotlight or a shadow is varied so that it covers more or less of the display, object lightness is altered. In the case of the narrow spotlight, a small region of the object is in the highest illumination (spotlight region) but the other part is in the largest area (i) in the global scene, (ii) on the display, and (iii) on each rectangle. Therefore, object lightness is solely determined by area. In the thick-shadow condition, one region of the object (the patch in the room illumination) is in the highest illumination and the largest area of illumination in the global scene. All things being equal, this patch would drive object lightness. However, the other region (the patch in the shadow) is in the largest area of illumination both on the display and on each rectangle. Consequently, object lightness is a compromise between the lightness values for the patches.

Finally, area on each rectangle was tested. When the relative area of higher and lower illumination on the object is varied, object lightness is again influenced. This was demonstrated in the zig-zag display, partially covered with spotlight (experiment 7). Object lightness for rectangles mostly covered with the room illumination was a compromise between patches in the highest illumination (spotlight) and those in the largest area of illumination, both on the object and in the scene. But for the neighboring rectangle, mostly covered by the spotlight, object lightness was based only on the patch in spotlight. Naturally so, because in that case the patch in the spotlight is both under the highest illumination and has the largest area on the object (even though it is not part of the largest area in the whole scene).

Another conclusion coming from these experiments is that the area that plays a role in largest-area rule is not some absolute, a priori given area. It is the area relative to the other areas in the visual scene. The comparisons among the results for center spotlight (experiment 3), narrow spotlight (experiment 4), and display on the wall (experiment 5) show the importance of relative area. Although the spotlight areas are equal in the center spotlight and display on the wall, the results are very different. The spotlights in the two experiments have the same absolute but not the same relative area. When the display is part of the wall, the spotlight, that previously covered half of the display, now covers only a small portion of the whole wall. On the contrary, the results are equal for narrow spotlight (experiment 4) and display on the wall (experiment 5). In these two experiments, the spotlights have different absolute areas but similar relative areas. The relative contribution of area in the global scene, area on each rectangle, and area on the display cannot be determined from the present experiments but is a topic for further research. Although regions of illumination can be defined in terms of figure and ground, we did not find a role in these experiments for these definitions.

Experiment 8 (spotlight/shadow) demonstrates the importance of the region of highest illumination. Largest area of illumination is neutralized because the spotlight area and the shadow area are equal (both on each object and on the display as a whole) and neither region is in the room illumination. In this case the visual system applies a single rule: make object lightness consistent with the lightness of the patch in the highest illumination.

Why would the visual system use these two rules? Perhaps because, on average, they would lead to more veridical percepts. The area of largest illumination is equivalent to Katz's laws of field size. It has been experimentally proven (Agostini and Bruno 1996; Cataliotti and Gilchrist 1995; Kardos 1935; Katz 1935; MacLeod 1932) that lightness constancy is better within a larger field of illumination. It has also been shown that, in general, there is a better acuity in higher illumination (König 1897). When acuity is better, it is likely that luminance ratios are encoded with greater accuracy as well. Thus the two rules may represent implicit knowledge by the visual system of the optimal conditions for seeing lightness. In fact, in most of the experiments in this study the two rules did produce the most veridical percept. In the first two shadow experiments (experiments 1 and 2), with no contradiction between the highest illumination rule and the largest illumination rule, object lightness tends to be determined by the patch that is closest to the actual values. In experiment 4 (narrow spotlight) and experiment 5 (display on the wall), where the largest area overrules the highest illumination, object lightness is again determined by the patch closest to the actual values.

These are fairly simple, unsophisticated rules and like other such rules [for example: light source above the observer's head (Ramachandran 1988)] they in fact sometimes lead to percepts that do not correspond to physical stimuli. For example the largest area of illumination rule does not provide veridicality in the situation where the illumination framework is large and well articulated but contains only dark-gray surfaces (Gilchrist et al 1999). In that case dark-gray surfaces are perceived as light-gray surfaces. However, this does not occur very often in the real world because natural scenes usually contain a full range of gray shades, especially when articulation is high.

The two rules proposed in this study are strikingly parallel to the two basic rules given by anchoring theory (Gilchrist et al 1999) for computing lightness: the highest luminance rule and the area rule. In both cases both a photometric factor and a geometric factor are maximized. Does this similarity have a deeper significance? In the lightness domain, the two rules are used to establish an anchor on the lightness scale. The rules we have found that relate object and patch matches might reflect an anchoring solution as well: perhaps the visual system is trying to establish a normalized level of illumination.

The present study derived its meaning within the basic approach of anchoring theory. The results we obtained for patch matches are highly consistent with the predictions from anchoring theory. But, until now, anchoring theory has not been able to predict the lightness of multi-lit objects. The two rules uncovered in this study suggest an extension of the theory that would allow such prediction. The extension would apply only to multi-lit surfaces—surfaces that are intersected by a framework boundary (illumination edge). When relative area is neutral (when equal proportions of the surface lie in the two frameworks, and when the two frameworks are roughly equal in area) the lightness of the surface will be the same as for its patch lying in the higher illumination. However, asymmetries in relative area can alter this outcome, but only when that asymmetry favors the lower illumination. When the part of the surface lying in lower illumination is larger in area than the part in higher illumination, or when the whole region of lower illumination is larger than the region of higher illumination, then the lightness of the whole surface will shift toward the lightness of its shadowed part, that shift being proportionate to the degree of asymmetry in area.

Recently Bressan proposed another version of anchoring theory (Bressan 2006a, 2006b) redefining some old concepts (area rule into surround rule) and introducing some new concepts (overlay framework). We have not attempted to evaluate what that model would predict in these experiments.

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**References**

Adelson E H, Pentland A P, 1996 "The perception of shading and reflectance", in *Perception as Bayesian Inference* Eds D Knill, W Richards (New York: Cambridge University Press) pp 409 – 423

Agostini T, 2003 "Luce, ombra e colore: i fatti oltre le parole", in *Figura e Sfondo: Temi e Variazioni per Paolo Bozzi*, a cura di U Savardi, Ed. A Mazzocco (Padua: CLEUP) pp 155 – 162

Agostini T, Bruno N, 1996 "Lightness contrast in CRT and paper-and-illuminant displays" *Perception & Psychophysics* **58** 250 – 258

Barrow H G, Tenenbaum J, 1978 "Recovering intrinsic scene characteristics from images", in *Computer Vision Systems* Eds A R Hanson, E M Riseman (Orlando, FL: Academic Press) pp 3 – 26

Bergström S S, 1977 "Common and relative components of reflected light as information about the illumination, colour, and three-dimensional form of objects" *Scandinavian Journal of Psychology* **18** 180 – 186

Bressan P, 2006a "The place of white in a world of greys: A double-anchoring theory of lightness perception" *Psychological Review* **113** 526 – 553

Bressan P, 2006b "Inhomogeneous surrounds, conflicting frameworks, and the double-anchoring theory of lightness" *Psychonomic Bulletin & Review* **13** 22 – 32

Cataliotti J, Gilchrist A L, 1995 "Local and global processes in lightness perception" *Perception & Psychophysics* **57** 125 – 135

Economou E, Annan V, Gilchrist A, 1998 "Contrast depends on anchoring in perceptual groups" *Investigative Ophthalmology & Visual Science* **39**(4) S857 (abstract)

Gilchrist A, 1979 "The perception of surface blacks and whites" *Scientific American* **240**(3) 112 – 123

Gilchrist A, Delman S, Jacobsen A, 1983 "The classification and integration of edges as critical to the perception of reflectance and illumination" *Perception & Psychophysics* **33** 425 – 436

Gilchrist A, Kossyfidis C, Bonato F, Agostini T, Cataliotti J, Li X, Spehar B, 1999 "An anchoring theory of lightness perception" *Psychological Review* **106** 795 – 834

Helmholtz H von, 1867/1924 – 1925 *Treatise on Physiological Optics* English translation by J P C Southall for the Optical Society of America (volume 1, 1924; volumes 2 and 3, 1925) from the 3rd German edition of *Handbuch der physiologischen Optik* (first published in 1867, Leipzig: Voss)

Kardos L, 1934 *Ding und Schatten* [Object and Shadow]. *Zeitschrift für Psychologie* Ergänzungsband 23

Katz D, 1935 *The World of Colour* (London: Kegan Paul, Trench, Trubner & Co)

König A, 1897 "Die Abhängigkeit der Sehschärfe von der Beleuchtungsintensität" *Sitzberichte der Akademie für Wissenschaften* **35** 559 – 575

Li X, Gilchrist A, 1999 "Relative area and relative luminance combine to anchor surface lightness values" *Perception & Psychophysics* **61** 771 – 785

MacLeod R B, 1932 "An experimental investigation of brightness constancy" *Archives of Psychology* **135** 5 – 102

Nakayama K, Shimojo S, 1990 "Da Vinci stereopsis-depth and subjective occluding contours from unpaired image points" *Vision Research* **30** 1811 – 1825

Ramachandran V S, 1988 "Perception of shape from shading" *Nature* **331** 163 – 166

Rubin E, 1921 *Visuell wahrgenommene Figuren* (Copenhagen: Gyldendalske)

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